OCO-2 In-Orbit Checkout Status

Dave Crisp, OCO-2 Science Team Leader

California Institute of Technology, Jet Propulsion Laboratory

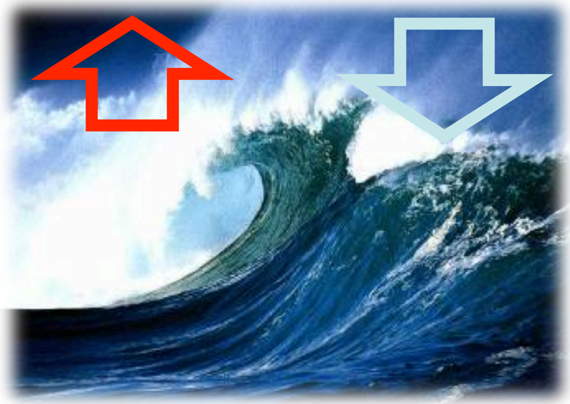
For the OCO-2 Team

10/1/2014

What Controls Atmospheric Carbon Dioxide?

Natural systems including the ocean and plants on land both absorb and emit CO_2 to the atmosphere

- Each year, the Land Biosphere
  - emits ~120 Billion tons carbon **(~440 Gt CO_2)**
  - reabsorbs ~122 Billion tons carbon **(~450 Gt CO_2)**
- Each year, the Ocean
  - emits ~90 Billion tons carbon **(~330 Gt CO_2)**
  - reabsorbs ~92 billion tons carbon **(~340 Gt CO_2)**

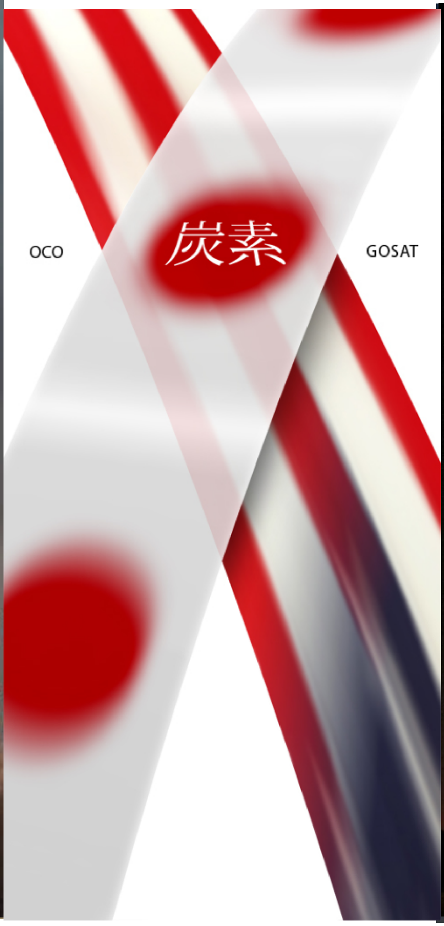


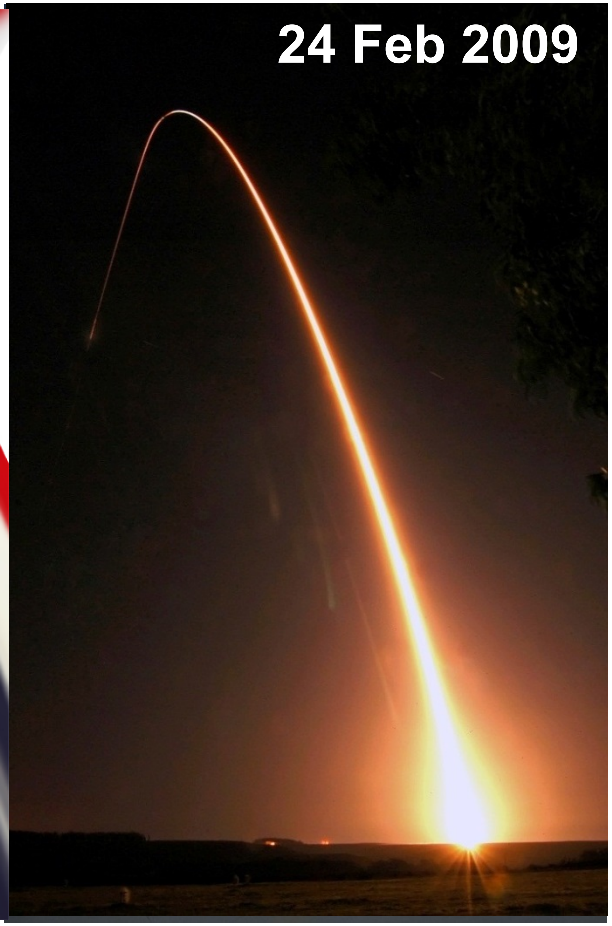
Currently, these natural systems are

- absorbing about half of the **40 Gt CO_2** emitted by human activities
- limiting the rate of carbon dioxide buildup and its impact on the Earth's climate

The Pioneers: GOSAT and OCO

Space based measurements provide new tools for measuring CO_2

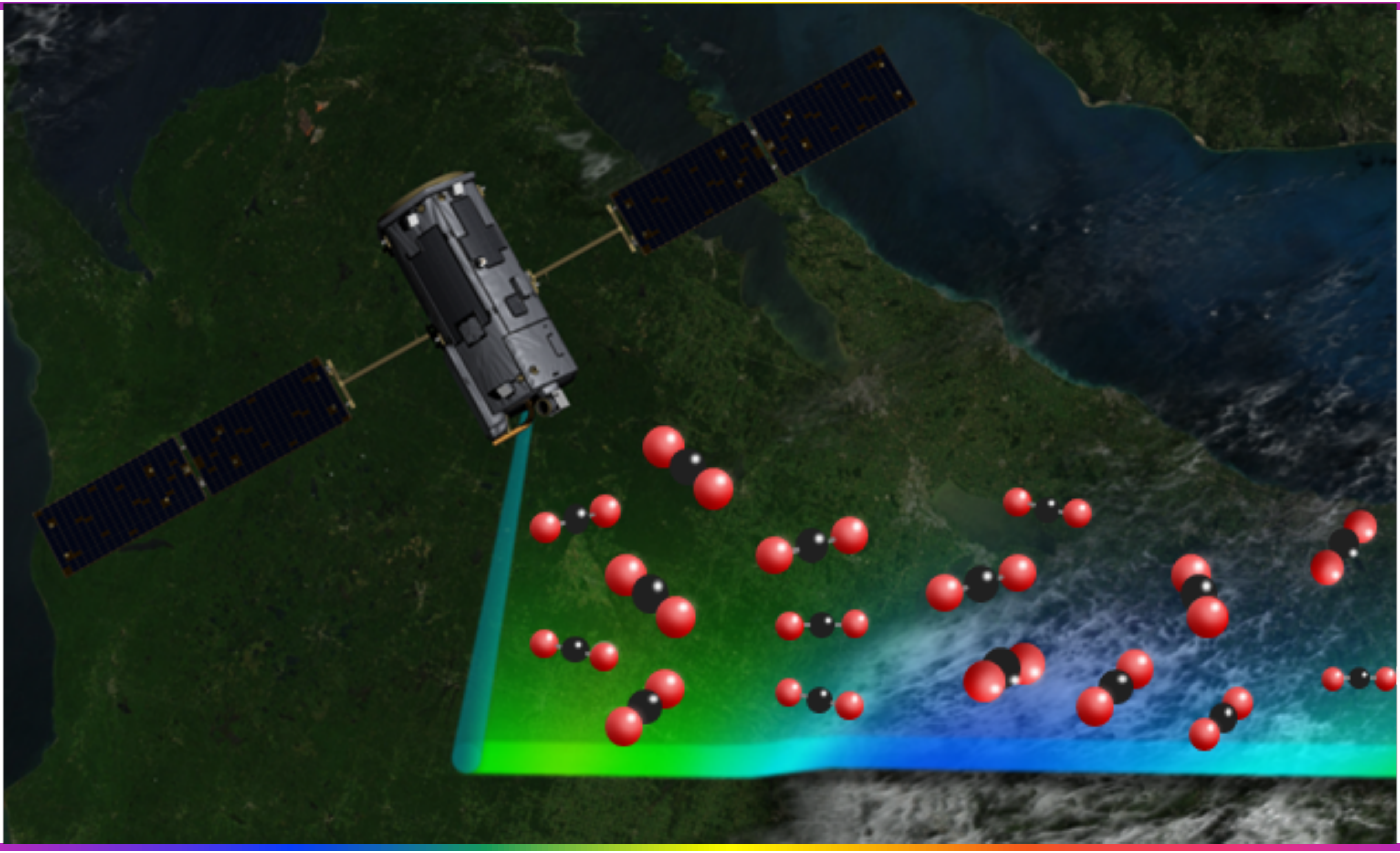




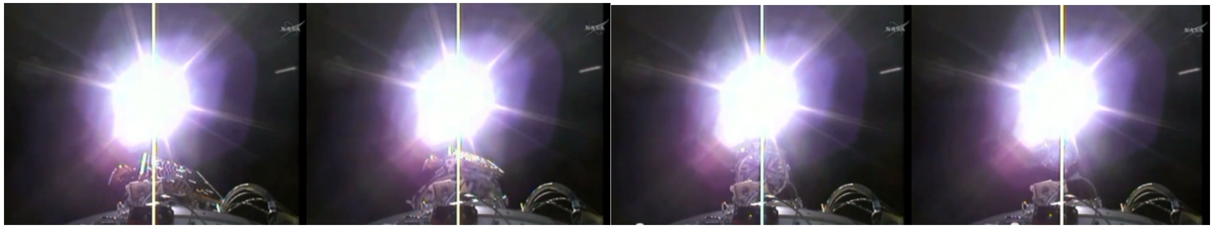
GOSAT launched successfully on 23 January 2009

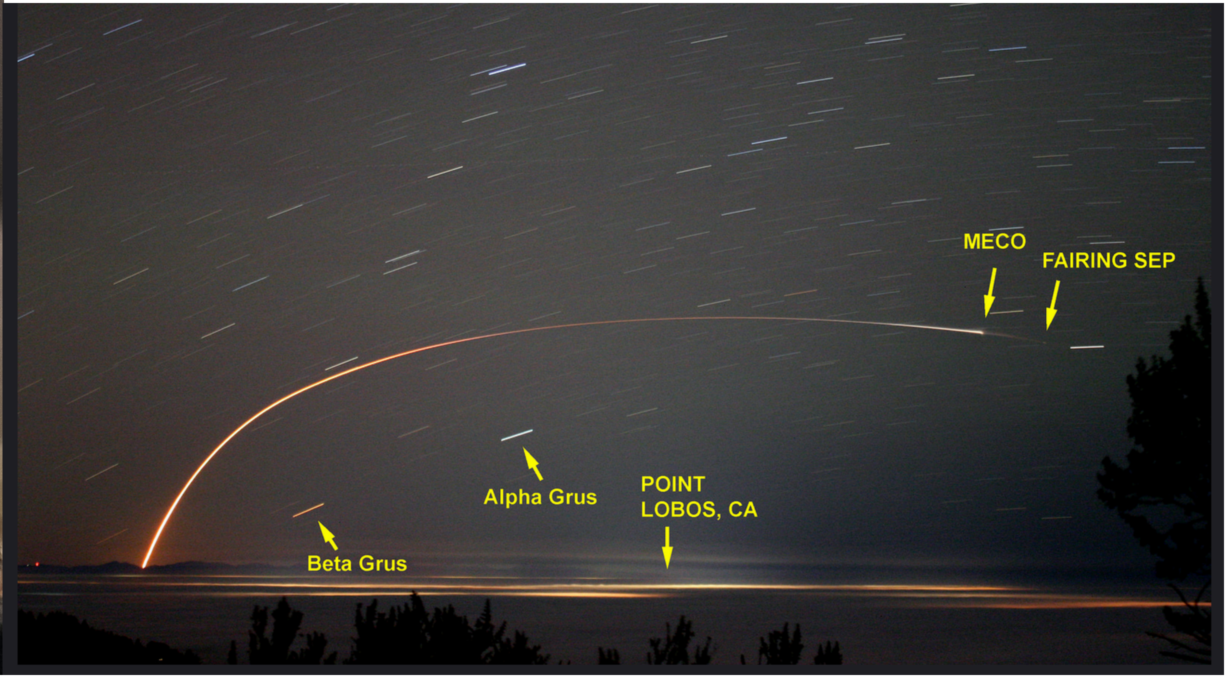
OCO was lost a month later when its launch system failed

The Next Step - The NASA Orbiting Carbon Observatory-2 (OCO-2) Mission



July 2, 2014, 2:56 AM PDT





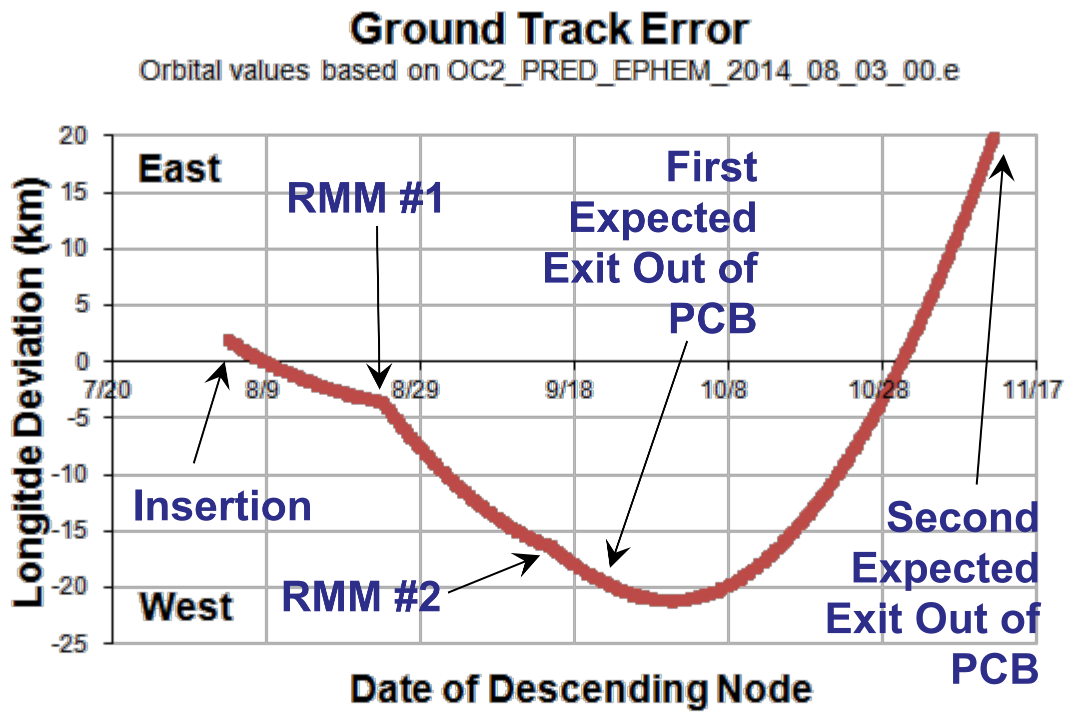
Overview of In-Orbit Checkout (IOC)

- IOC includes three primary phases:
  - Initial spacecraft checkout – completed 7/8/2014
  - Orbit raising and A-Train insertion – completed 8/3/2014
  - Instrument checkout and calibration – ongoing
- The current phase includes three primary activities
  - Instrument / observatory operations
    - Commanding, cryocooler operation, temperature stability, pointing, etc.
  - Instrument calibration
    - Darks, lamp flats, bad pixel map updates, solar calibration, Railroad Valley observations, lunar observations, etc.
  - L1B Product generation and validation
    - Verification of instrument calibration information and instrument model

OCO-2 Navigation Status

Current Orbit Properties:

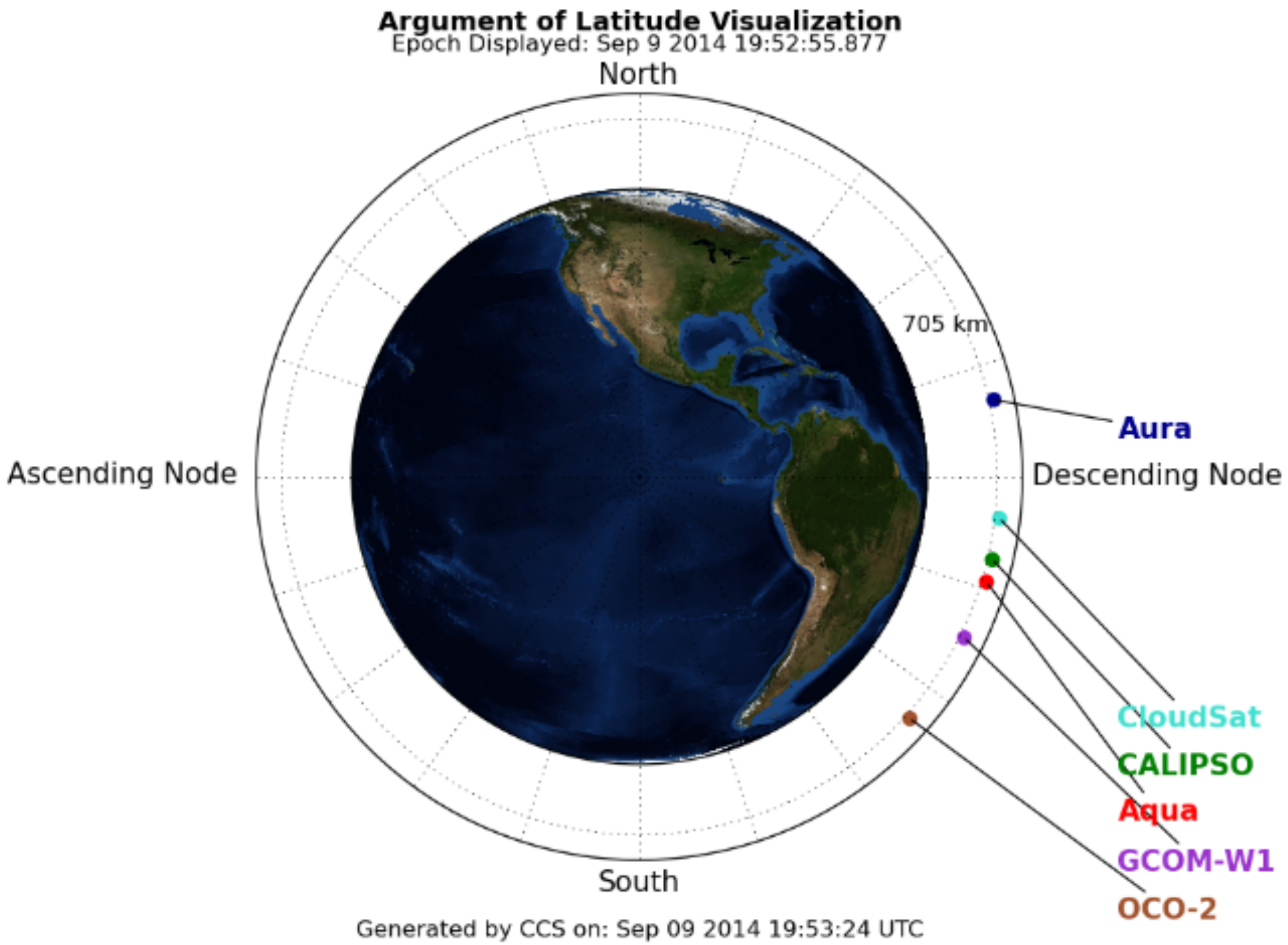
- The observatory was inserted 2.1 km East of its Reference Ground Track (RGT) on 3 Aug.
- On 9/18, it was 17.5 km West of its RGT and drifting toward the western edge of its Phase Control Box (PCB)
  - Mean SMA = 7077.788 km
  - MLTAN = 13:36:00
- Given current solar flux and drag predictions, the observatory will exit the PCB by a small amount on 23 September and re-enter on 8 October



Location in PCB since 3 August 2014.

Orbital Debris: The team continues to identify and track orbital debris. Potential collisions are identified daily and risk mitigation maneuvers are performed roughly once each month.

OCO-2 Navigation Status

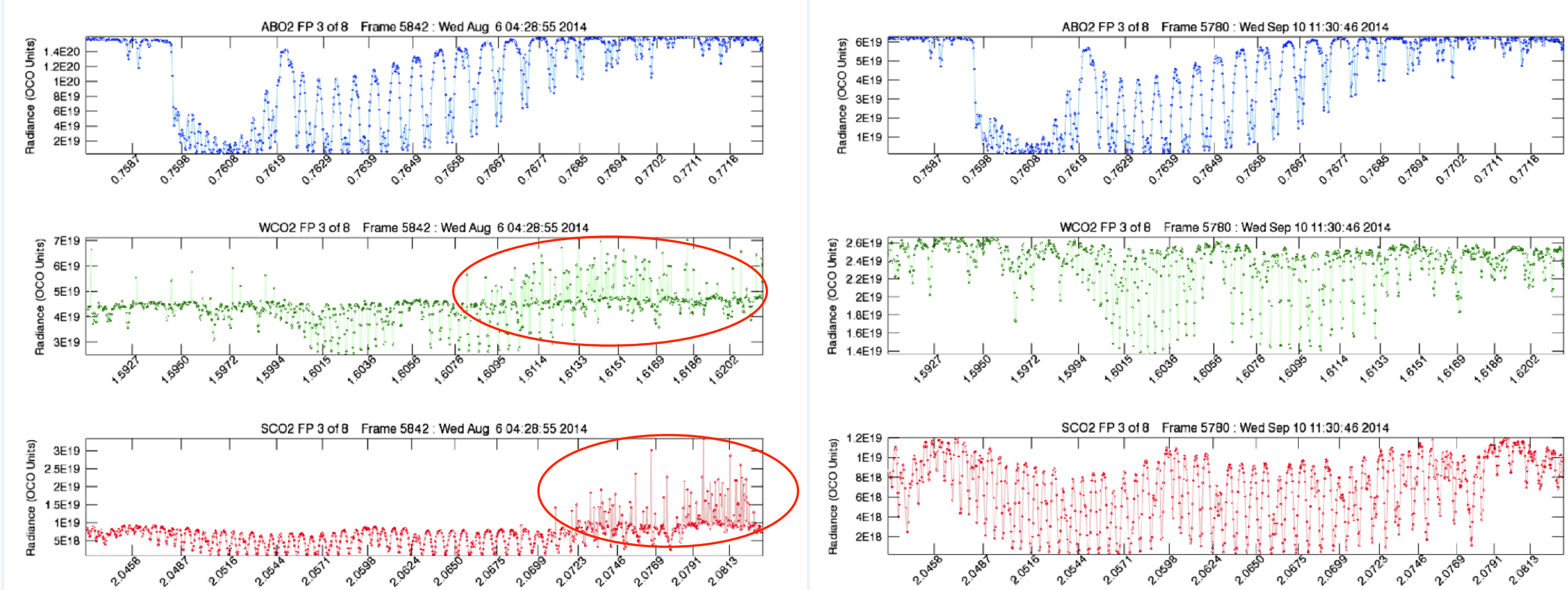


OCO-2 crosses the equator at 1:36:00 PM. About 180 seconds later, it is followed by the Japanese GCOM-W1 satellite, which, in turn is followed about 260 seconds later by the NASA Aqua platform. The CALIPSO, CloudSat, and Aura satellites then follow (spaced at 73, 103, and 273 seconds, respectively), bringing up the tail of the A-Train.

Examples of Calibration Progress

- Dark Calibration, Lamp Flats, and Bad Pixel Maps
  - An accurate estimate of the bias level, noise, and gain for each pixel on the focal plan arrays (FPA's) needed for radiometric calibration
    - The FPA dark response changes every time the FPA's are cycled from room temperature to operating temperature (120 K).
- Lunar Calibration
  - Observations of the Moon provide information about:
    - Relative pointing of the star tracker and instrument field of view
    - Relative alignment of the slits of the 3 spectrometers
    - Absolute radiometric response of the 3 spectral channels
- Solar Doppler
  - Diffuse sunlight is observed over a full dayside orbit to sample all Doppler shifts and characterize the instrument line shape (ILS) function

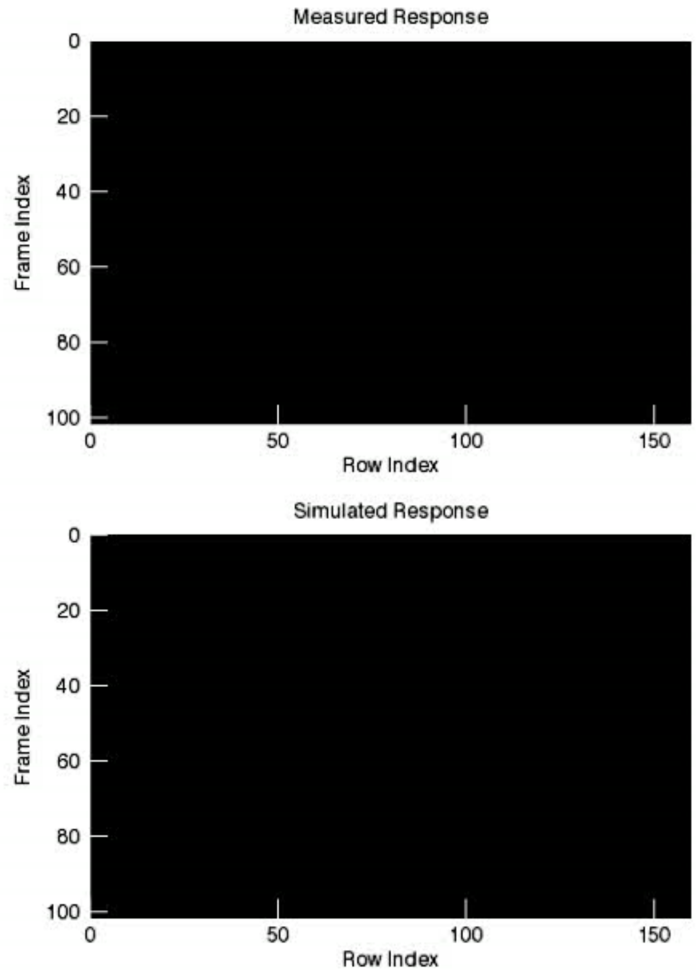
Dark Calibration



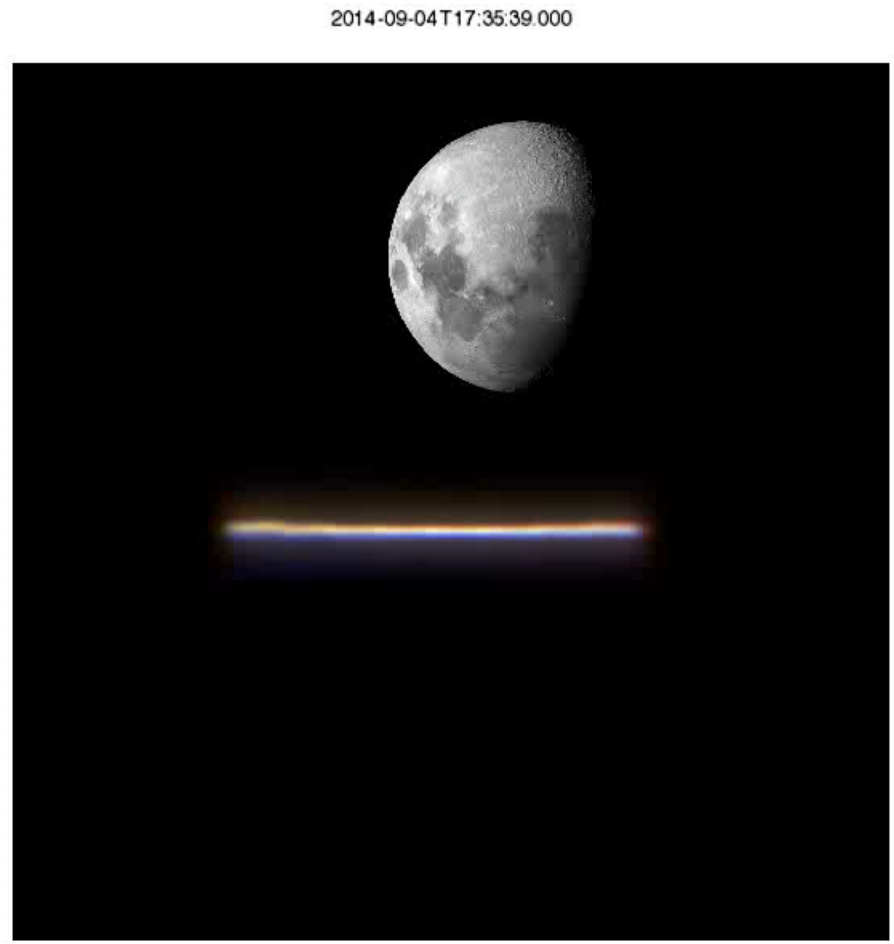
Rob Rosenberg & Randy Pollock

Spectra recorded in the O_2 A-band (top), Weak CO_2 Band (middle) and Strong CO_2 band (bottom) on August 8 (left) and September 10 (right) show the impact of improved dark calibration. The August 8 spectra were calibrated using focal plane array dark response recorded during the pre-launch thermo-vacuum tests at JPL in 2012. The September 10 spectra were calibrated using dark data recorded on orbit. The revised dark data dramatically improves the quality of the spectra at longer wavelengths in the Weak CO_2 and Strong CO_2 channels.

Lunar Calibration Animation



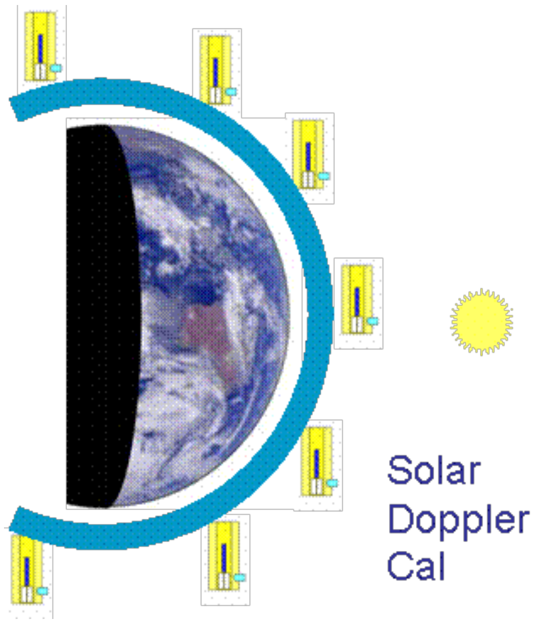
Measured Response

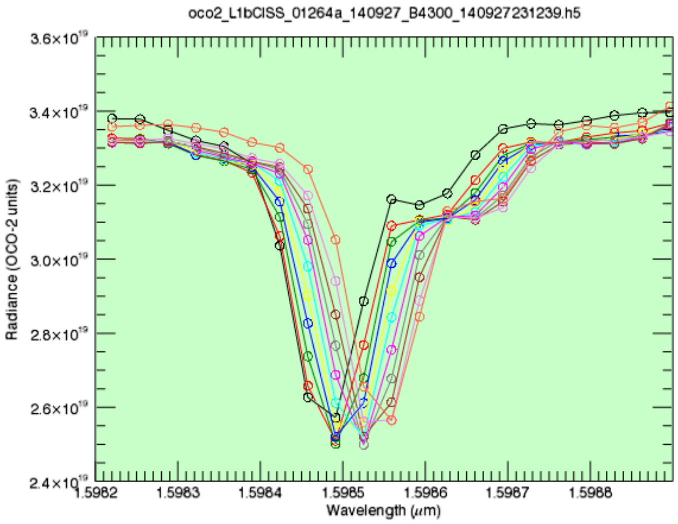


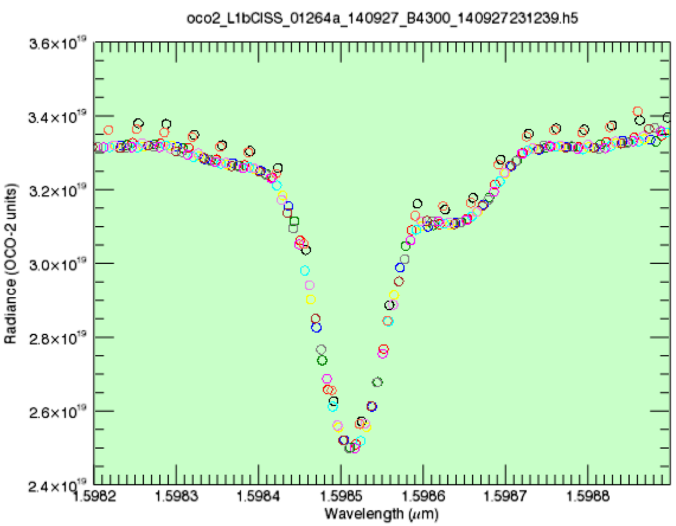
Simulation

Lars Chapsky & Randy Pollock

Solar Doppler







- Measurements of diffuse sunlight are collected over a complete dayside orbit
- These measurements sample the solar spectrum over the full range of Doppler shifts
- They can then be combined to provide a high resolution description of the Instrument Line Shape (ILS) function

Incidents, Surprises, and Anomalies

- As in all missions, the OCO-2 in-orbit checkout activities have revealed a few issues, surprises, and anomalies, including:
  1. Unexpectedly high signals recorded in glint observations
     - Observations of Lake Maracaibo, Venezuela saturated all 3 channels
  2. Polarization Orientation Anomaly
     - The orientation of polarized component of the reflected sunlight accepted by the instrument is rotated 90 degrees from that intended
       - dramatically reduces the signal from the surface near the Brewster's angle (53° solar zenith angle)
       - Over land, this poses both advantages and disadvantages
     - Mitigation approach: Modify observing strategy for glint observations by rotating spectrometer slit with respect to the principle plane

Lake Maracaibo Incident

1. The Lake Maracaibo Incident

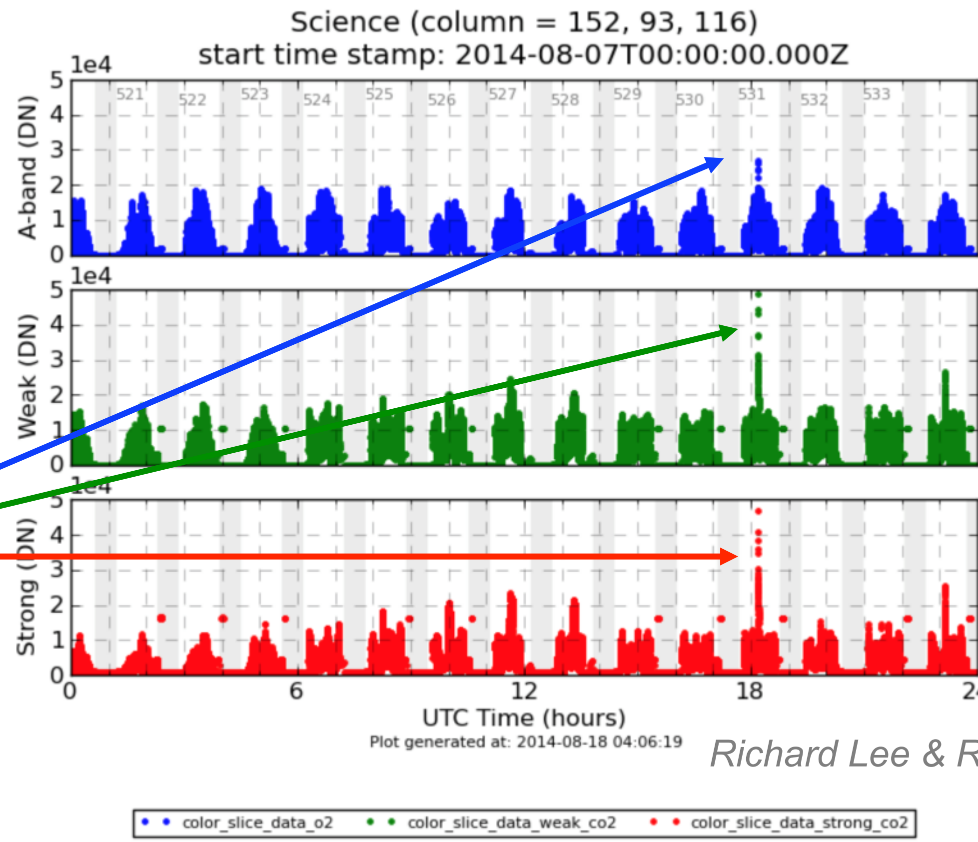
- An unexpectedly bright reflection off Lake Maracaibo in Venezuela saturated all 3 detectors, leading to concerns about instrument safety
  - The solar diffuser was put in place as a precautionary measure
    - the H1RG HyViSi focal plane array (FPA) used in the O_2 A-band channel could be damaged by large overexposures (50x full well)
    - The HgCdTe Hawaii-1RG FPA's in the two CO_2 channels have much larger damage thresholds
  - A comprehensive investigation was initiated
    - Unexpected brightness attributed to an oil slick on a wave-free lake
    - The observed intensities were at least a factor of 5 smaller than those needed to damage the FPA in the O_2 A-band
  - Changes to the glint pointing offset were considered, but then rejected since the incident posed no danger to the system, and any change would reduce signal levels at high latitudes

Detecting the Lake Maracaibo Saturation Event

OCO-2 started Glint mode observations at 2014-08-07T06:17:03.000Z (orbit 524)

- On 2014-08-07 at about 18:00 UTC, we observed an anomalously bright event in the color slice data plotted by the engineering telemetry trending report

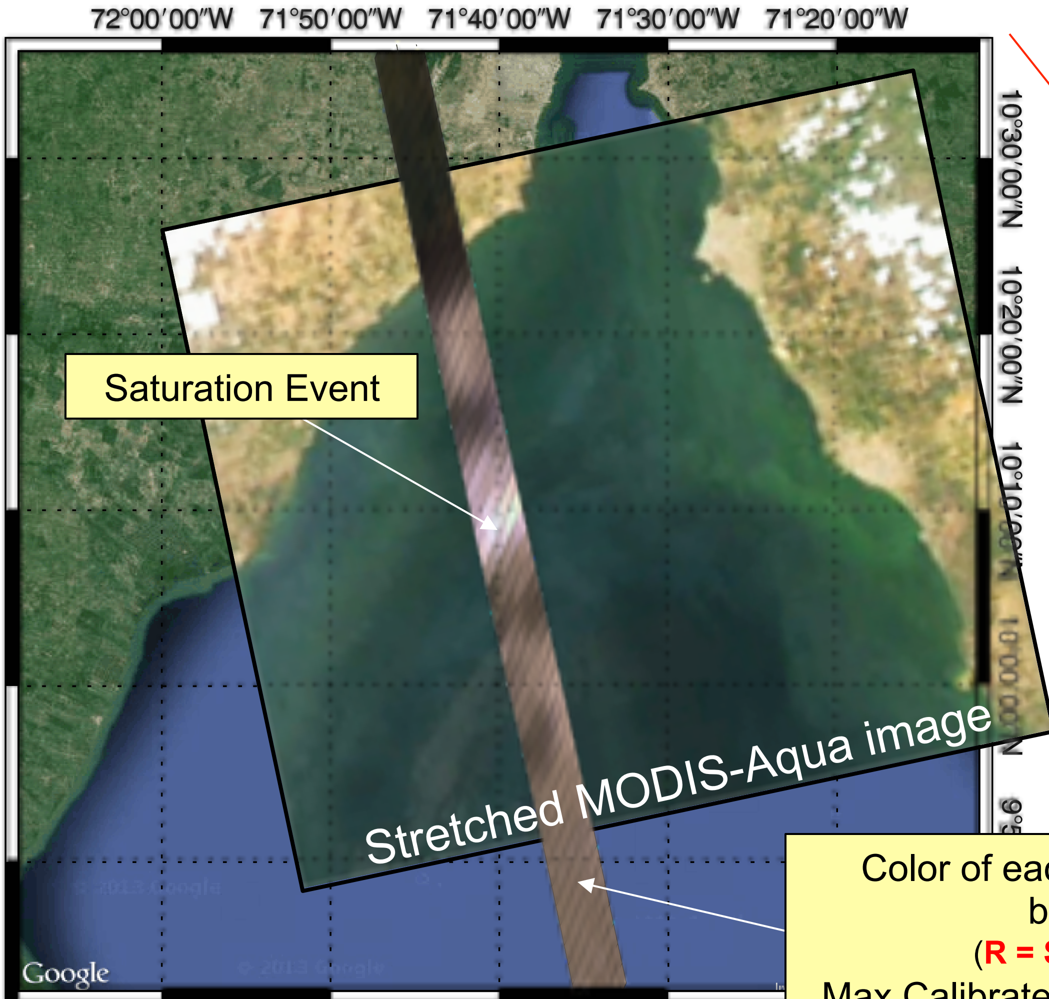
- This event is clearly seen in all three spectrometers



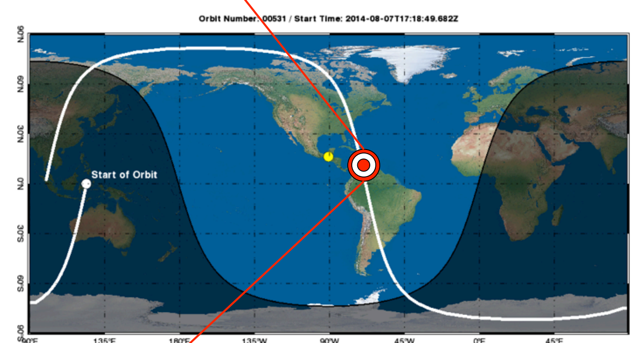
Richard Lee & Randy Pollock

Screen shot of the color slice monitoring panel of the OCO-2 calibration tracking tool. Color slice intensities (raw counts) in the O_2 A-band, Weak CO_2 band, and Strong CO_2 bands are shown for the 14 orbits recorded on 7 August 2014 (dark bands indicate eclipse).

Observed Radiance over Lake Maracaibo



- Place:
  - Lake Maracaibo, Venezuela
- Date and Time:
  - 7 August 2014
  - 18:11:00.666 UTC



Color of each footprint is RGB using continuum brightness in each channel
(**R = Strong**, **G = Weak** & **B = A-band**)
Max Calibrated Radiance or greater shown as white

Randy Pollock

Lessons Learned from the Lake Maracaibo Saturation Incident

- The incident prompted a comprehensive review of the focal plane array (FPA) calibration limits, saturation levels, and damage thresholds
  - Only the O_2 A-band FPA can be damaged by anything less than direct, prolonged observations of the sun
  - The observed intensities over Lake Maracaibo were at least a factor of 5 smaller than those needed to damage the O_2 A-band FPA
- The incident also accelerated the validation of the glint pointing, geolocation, and intensity prediction algorithms
- An automated saturation warning algorithm has been incorporated into the instrument trending tool to identify saturation events
- Unintended Glint Observation during Target Observations
  - As part of this investigation, we found that the observatory occasionally points directly at the glint spot during it slew to some surface targets
  - Screening software was developed to identify these targets

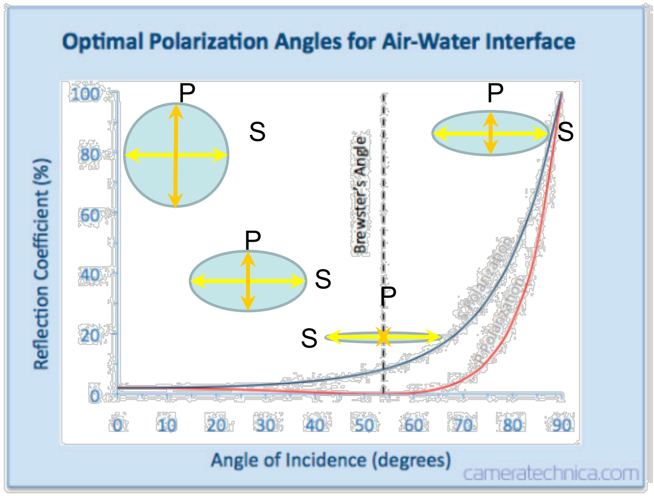
Polarization Orientation Anomaly

2. Polarization Orientation Surprise

- The orientation of polarized component of the reflected sunlight accepted by the instrument is rotated 90 degrees from that intended
- If the spacecraft continues to fly with the slit oriented perpendicular to the principal plane, this polarization rotation changes to the information content of both Nadir and Glint observations
  - For glint measurements over the ocean, this issue dramatically reduces the signal from the surface, especially near the Brewster's angle (53 degrees)
  - For nadir observations over land, the impact on signal levels is much less severe, but this polarization rotation
    - Reduces the sensitivity to polarized (near-specular) surfaces
    - Minimizes the impact of Rayleigh scattering in the A-Band and scattering by cirrus clouds (which are usually strongly polarized)
- These issues can be mitigated by modifying the observing strategy

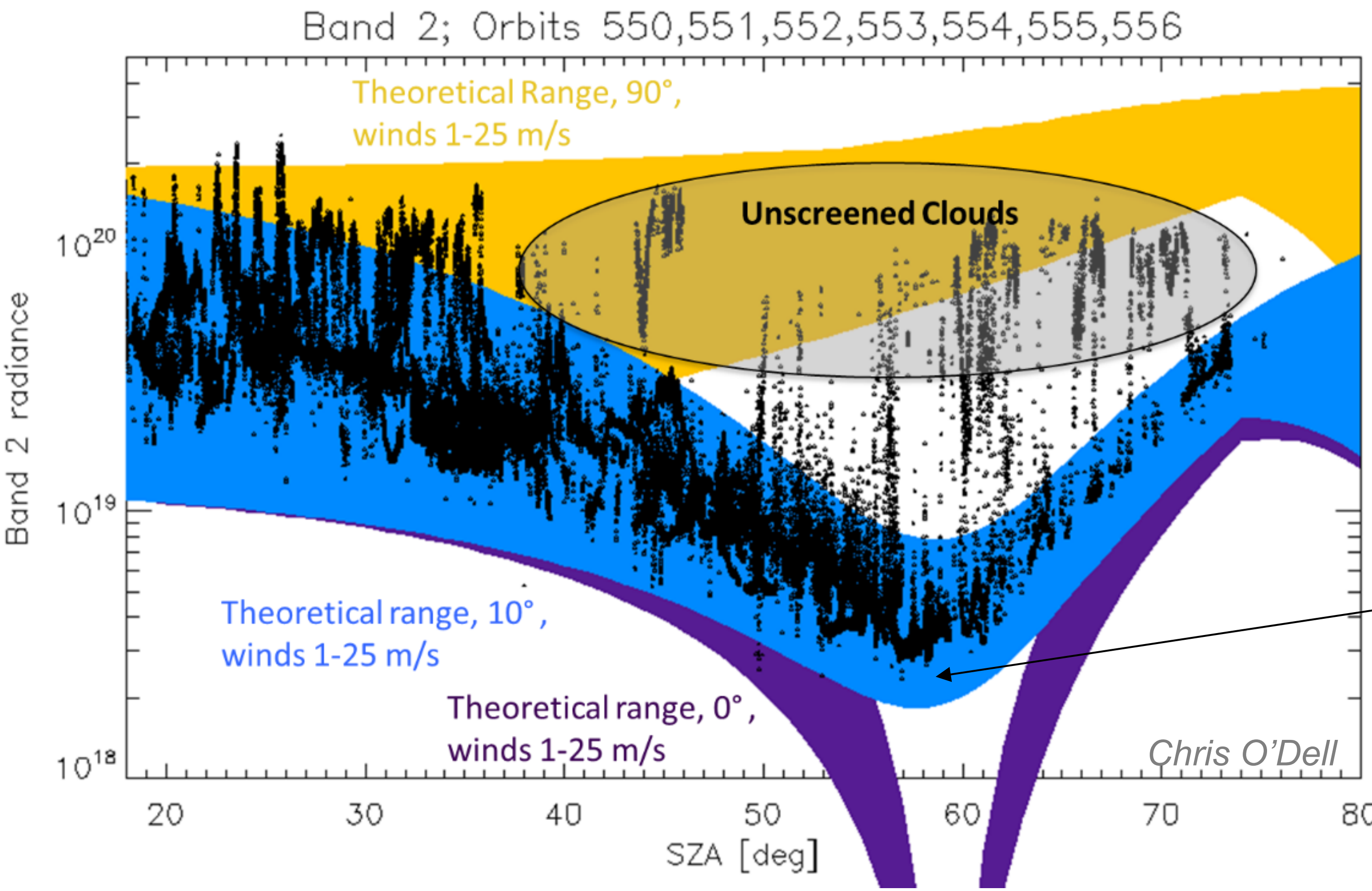
Polarization and the OCO-2 Measurements

- The main purpose of glint mode is to measure CO_2 over water, which is dark and specular at the near infrared wavelengths where OCO-2 observes
- In glint mode, the light collected by OCO-2 can be significantly polarized at larger solar zenith angles
  - The degree of polarization approaches 100% at the Brewster's angle (53° over seawater)
- Polarized light can be represented by a polarization ellipse, with a major (S Polarization) and minor (P Polarization) polarization axis
- The OCO-2 instrument was supposed to observe light polarized in the S Polarization orientation, the plane most efficiently reflected by the surface
- Unfortunately, as built, the instrument is sensitive to the P Polarization when the slit is oriented perpendicular to the principal plane
- In the P Polarization, the ocean reflects very little light at the Brewster's angle



Ocean reflection in P and S polarization as a function of incidence (solar zenith) angle
http://www.cameratechnica.com/2011/04/10/the-science-of-polarizing-filters/

The Impact of the Polarization Orientation on Ocean Glint Observations



Most of the signal detected at the Brewster angle may be contributed by thin clouds and aerosols, rather than the surface. These effects are not included in the Cox-Munk simulations here. The best fit for the10° yaw is most likely coincidental.

OCO-2 WCO2 radiances (black points) for glint observations over ocean from 7 ocean orbits. The "Theoretical Range" for 0°, 10° and the intended 90° polarization orientations was estimated using a Cox-Munk ocean reflection model at wind speed from 1 to 25 m/s.

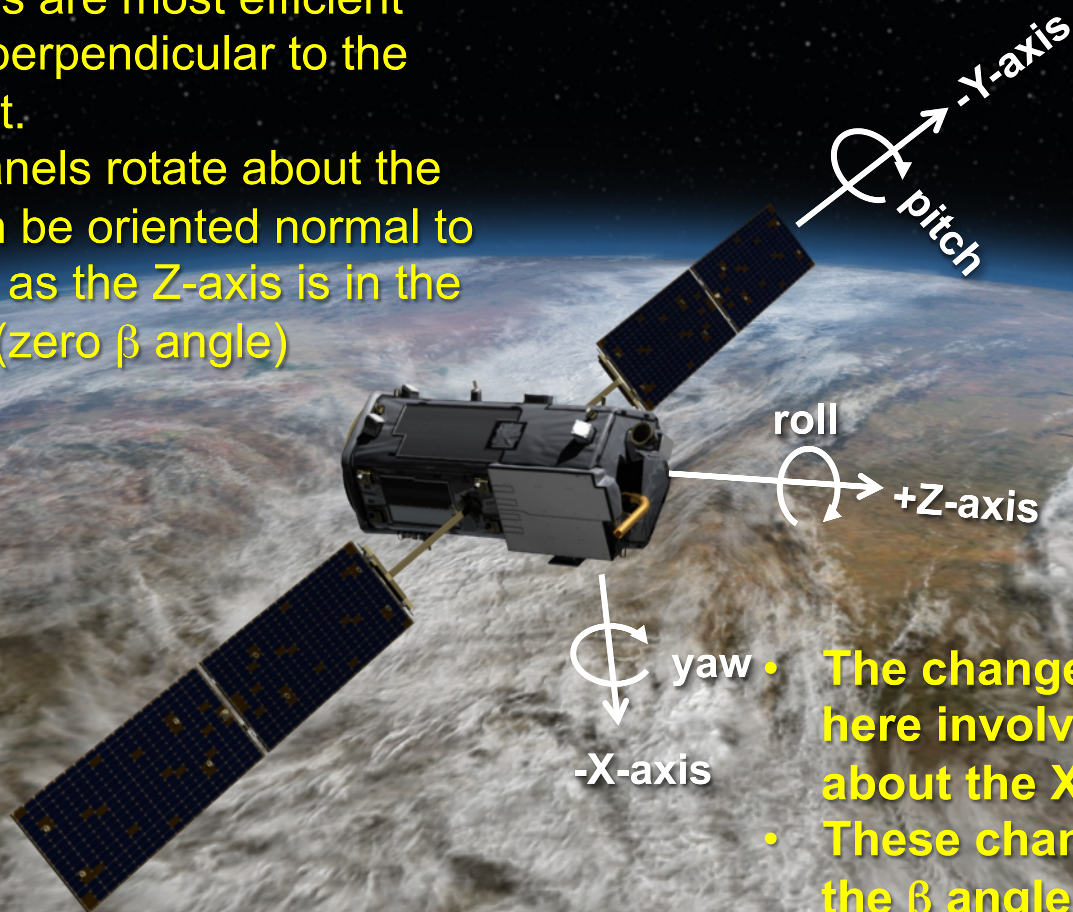
Options for Recovering Signal

1. ~~Reduce glint off-pointing angle to point closer to the glint spot~~
2. ~~Use a 90 degree yaw rotation in glint, 0 degree rotation in nadir on alternating orbits to manage the battery state of charge~~
   - ~~Full recovery of signal in glint, no change to nadir~~
   - ~~Each 90° glint orbit would have to be followed by a 0° yaw (glint/nadir) orbit~~
3. Use a 30 degree yaw rotation in glint (and nadir?)
   - Partial restoration of signal. Uniform sampling of the globe
   - introduces uncertainties in degree of polarization and radiometry
4. ~~Fly with the slit always perpendicular to the ground track~~
   - ~~Maximizes swath and and increases glint signal in north, but~~
   - ~~provides little advantage in south and may introduce along-track bias~~

Option 3 is the current focus of the mitigation effort.

Changing the Spacecraft Yaw: A Primer on Spacecraft Coordinates

- The solar panels are most efficient when they are perpendicular to the incident sunlight.
- Because the panels rotate about the Y axis, they can be oriented normal to the sun as long as the Z-axis is in the principal plane (zero β angle)



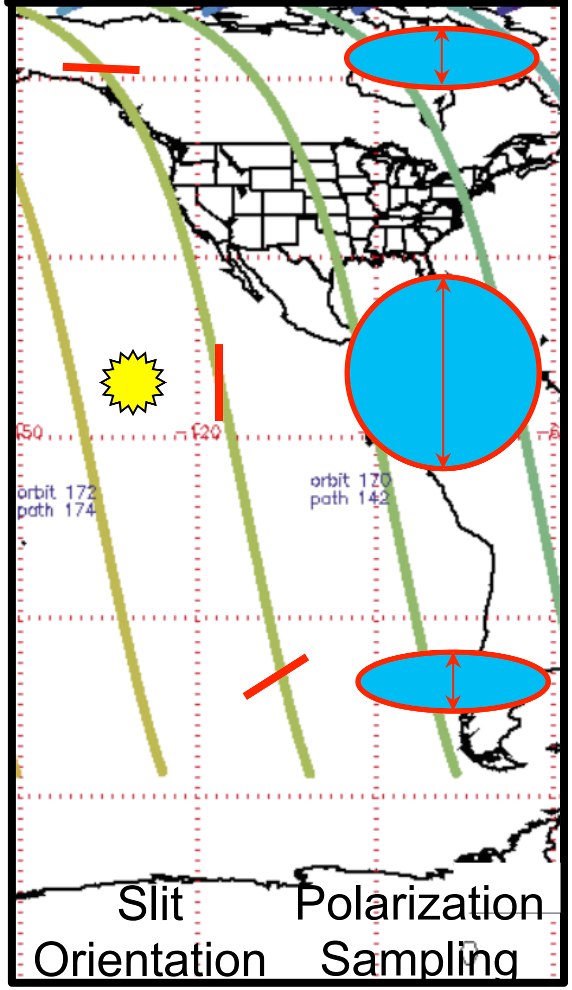
- **The changes considered here involve rotations about the X axis – "YAW"**
- **These changes increase the β angle and reduce the solar power available.**

Sarah Hunyadi-Lay & Randy Pollock

Science Impacts of Current Operational Mode

- As designed, in both Glint and Nadir modes operate with the Z-axis of the spacecraft pointed in the principal plane (i.e. : the plane containing the sun, spacecraft, and glint spot)
- In this orientation,
  – The single-axis solar array drive can maintain β=0 throughout the dayside orbit, maximizing power
    - the observatory has large power margins
  – The spectrometer slits remain perpendicular to principal plane, such that the swath width
    - is maximized near south and north terminators
    - Is minimum just north of the sub-solar latitude
  – This orientation provides no useful signal near the Brewster angle over the ocean in glint mode

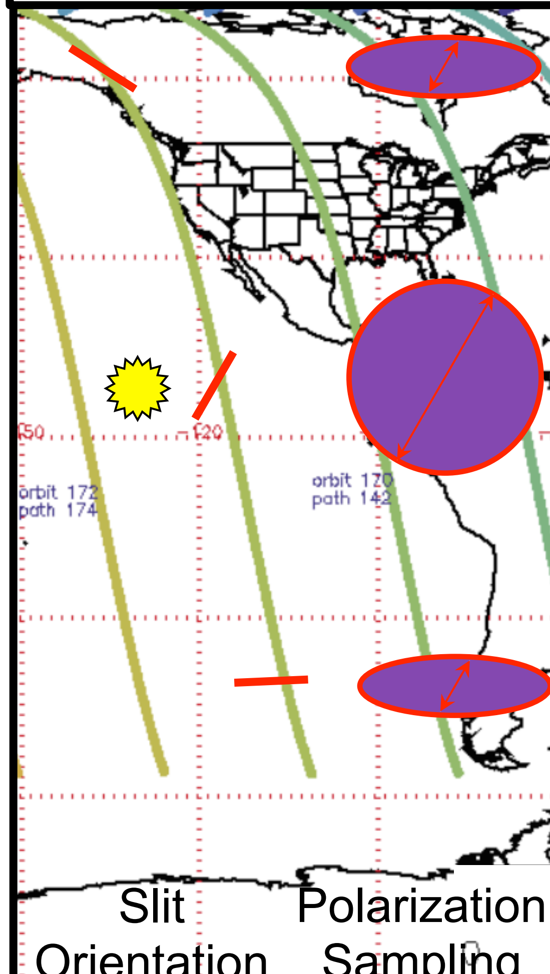
Slit Orientation and Polarization Sampling



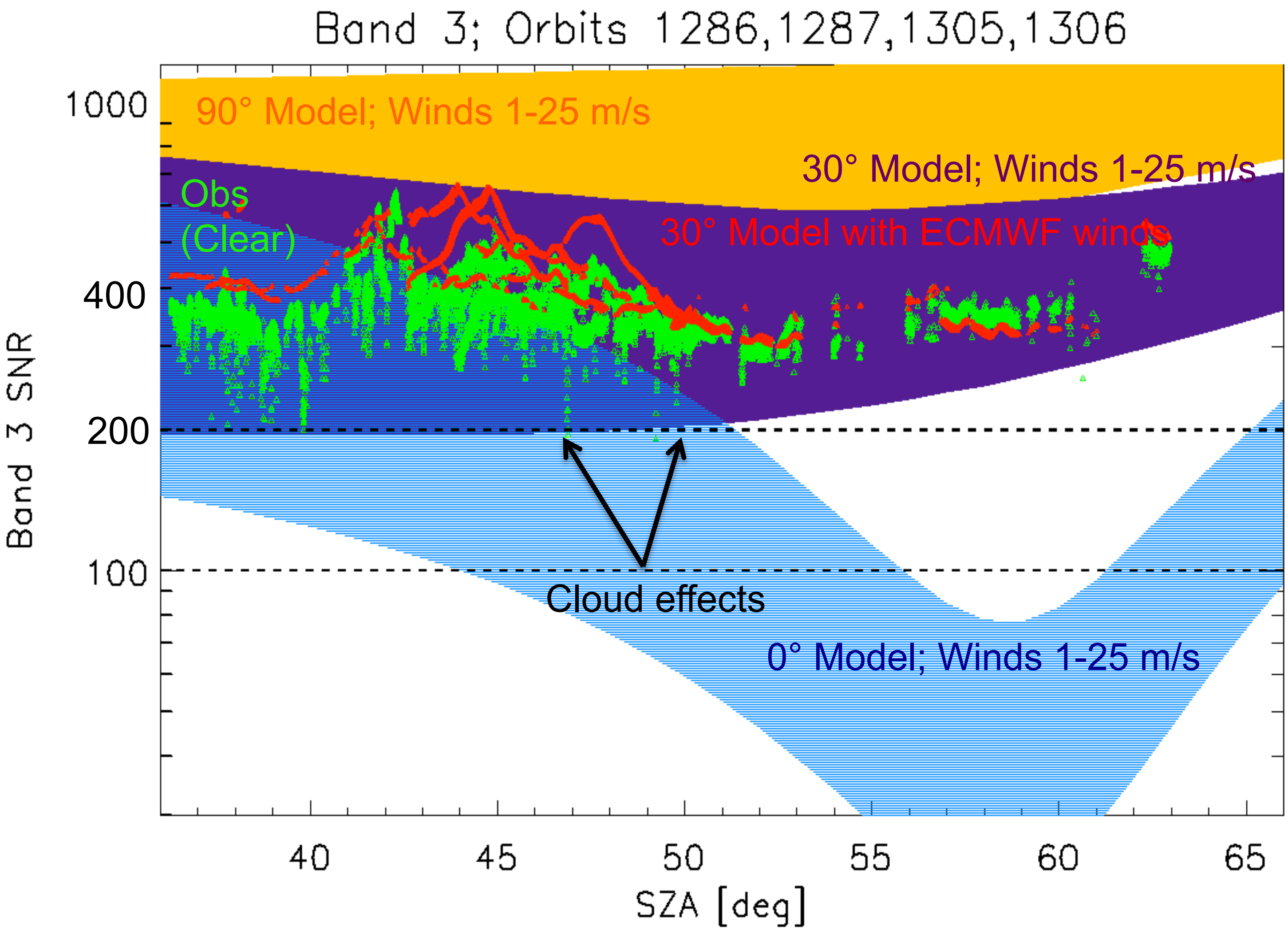
Science Impacts of Modified Strategy with a 30° Yaw Rotation in Glint

- Rotate (yaw) the spacecraft 30° around the instrument bore sight (-X axis) in glint
- This reorientation would
  - Increase glint Brewster angle signal to 25% of its intended values at the (SCO2 SNR > 200)
  - Increase the spectrometer's swath width south of the sub-solar latitude, but decrease it northward
  - Reduce the amount of sunlight absorbed by the solar panels but provide adequate power for continuous use in glint and nadir
  - Could introduce an SZA-dependent biases associated with uncertainties in polarization
- This is the option receiving the most attention

Slit Orientation and Polarization Sampling



30° Yaw Tests



Band 3; Orbits 1286,1287,1305,1306
90° Model; Winds 1-25 m/s
30° Model; Winds 1-25 m/s
Obs
(Clear)
30° Model with ECMWF winds
Cloud effects
0° Model; Winds 1-25 m/s
1000
400
200
100
Band 3 SNR
40
45
50
55
60
65
SZA [deg]

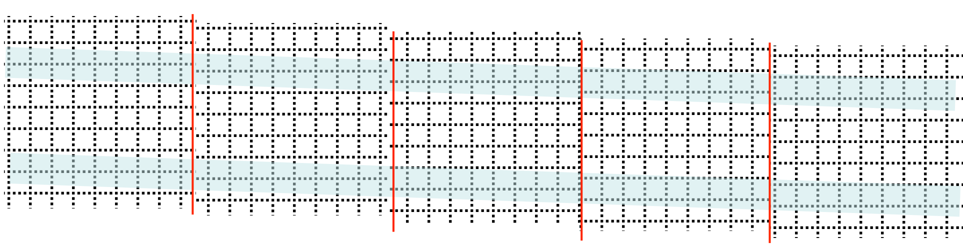
Mitigating the Impact of the Polarization Orientation Anomaly

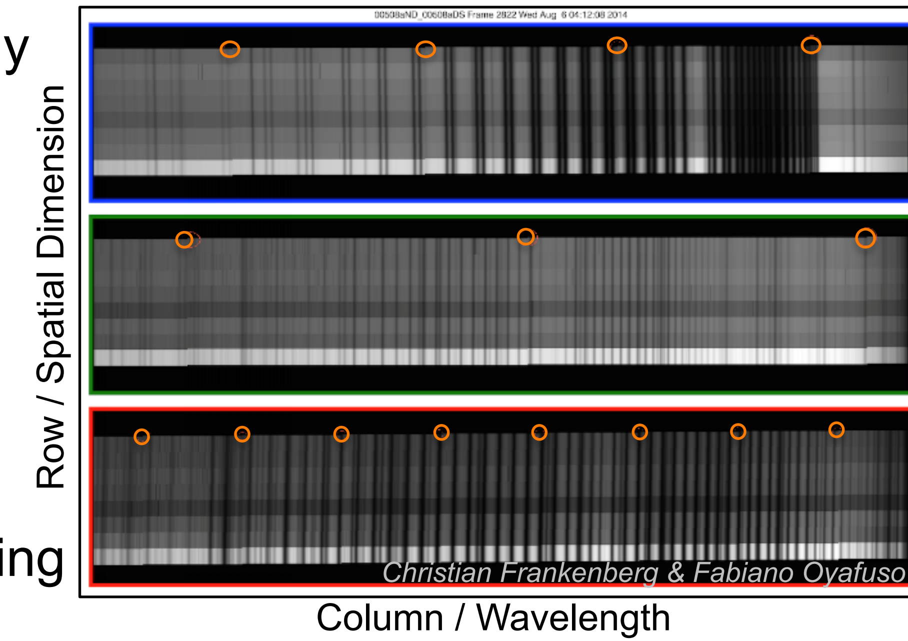
- The 30° yaw option in glint is the current focus of the polarization orientation anomaly mitigation plan
- Observations collected in “stellar” mode are being analyzed to confirm the 30° yaw in glint:
  - provides adequate sensitivity over the ocean at the Brewster angle in glint
  - preserves the single-orbit power budget
- The flight software is currently being modified to support a 30° yaw as the standard option for glint observations.
  - These changes will be implemented before the end of October
- The science team is performing simulations and analyzing data identify and correct any SZA dependent biases due to variations in degree of polarization along track in both glint and nadir

Calibration Challenges: Radiance Discontinuities due to Focal Plane Array (FPA) Rotation

FPA Clocking

- The OCO-2 FPA's are rotated slightly with respect to the slit and grating
- With these *FPA Clocking Errors,* the FPA rows recording a given spatial footprint varies across the spectral range (columns)
- To record the same spatial footprint across an entire spectrum, the starting pixel of each spatial footprint can be adjusted from one column (wavelength) to another (by one pixel)

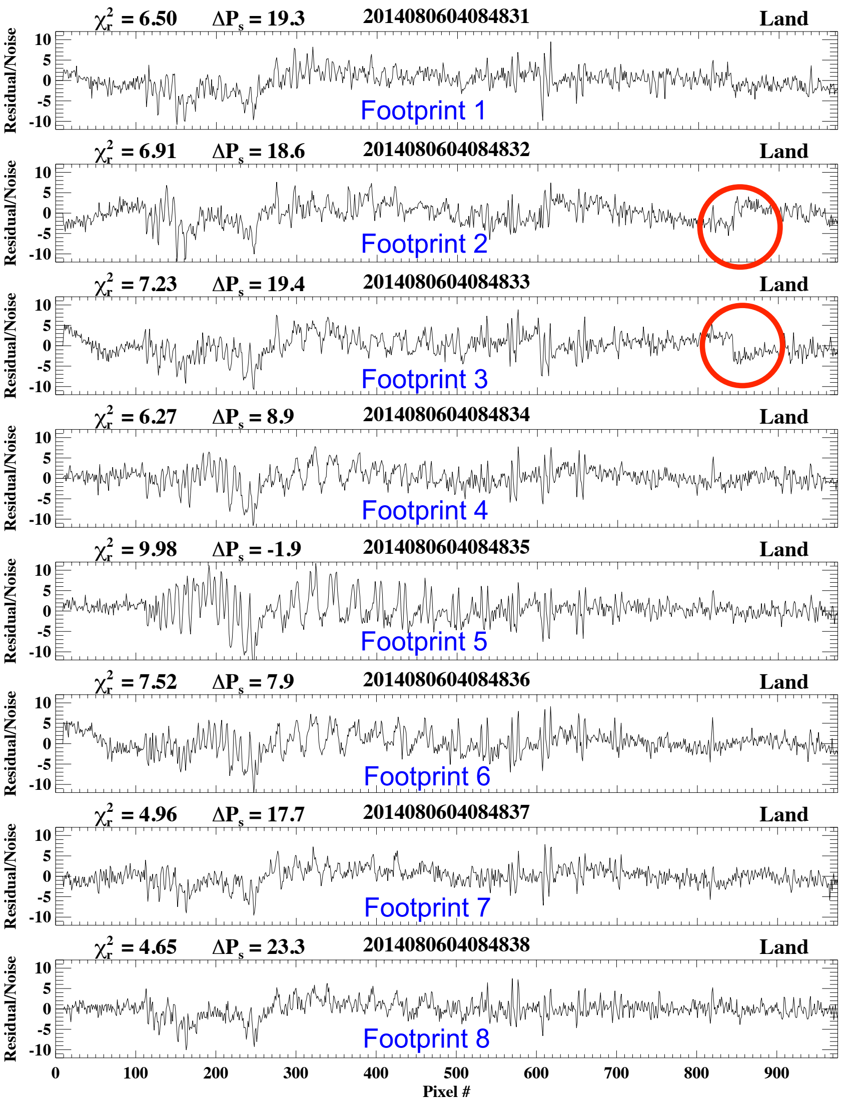




Images of the O_2 A-Band (ABO2, top), Weak CO_2 Band (WCO2, middle), and Strong CO_2 (SCO2, bottom) from the First Light frame are shown. Each footprint is sampled by ~20 single-pixel rows. The single-pixel offsets needed to record the same spatial footprint across the entire spectral range are circled. The SCO2 FPA has the largest clocking error and requires the largest number of corrections, followed by the ABO2 FPA.

Radiance Discontinuities due to FPA Clocking Errors

- If there is a discrete illumination anomaly near the edge of the footprint, a clocking offset can introduce discontinuities in the spectrum
- These discontinuities are most easily seen in spectral fitting residuals (image at right) but are occasionally large enough to be seen in raw spectra.
- The discontinuities often have mirror images in the adjacent footprints, as seen in footprints 2 and 3 in the image at right.

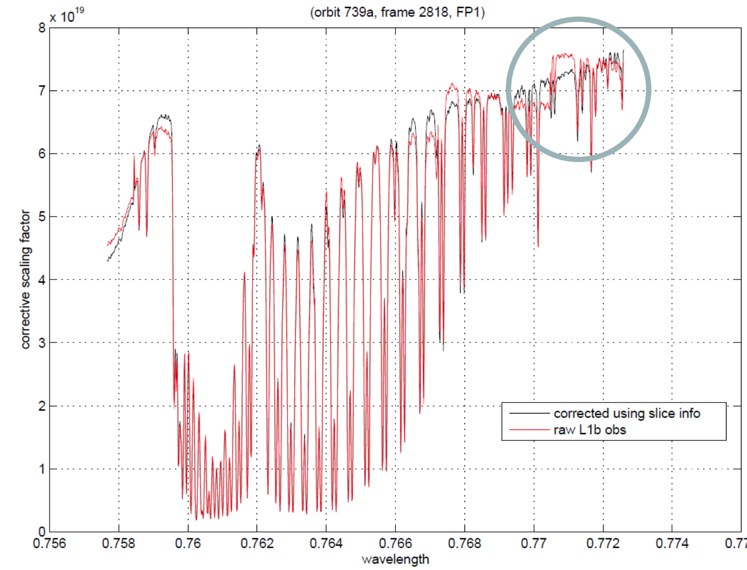


Christian Frankenberg, Chris O'Dell, & Fabiano Oyafuso

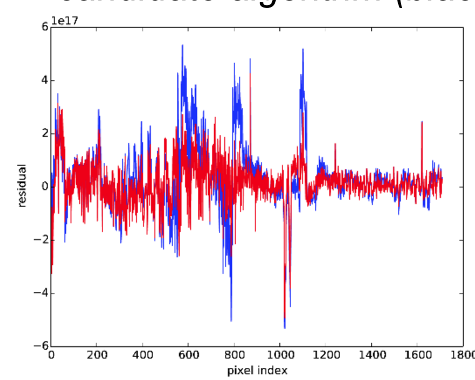
Correcting Radiance Discontinuities

- An algorithm that uses the high-resolution color slices to identify and correct for radiance discontinuities is currently under development
  - Color slices sample each spatial footprint with 20 pixels – read out at full resolution
  - Early tests are promising: most spectra require corrections smaller than 2%
  - The largest changes are needed in the SCO2 band, because it has the largest rotation.
- Additional tests are needed to refine the algorithm, optimize the positions of the color slices used, and asses its end-to-end performance in X_{CO2} retrievals.

Christian Frankenberg & Fabiano Oyafuso

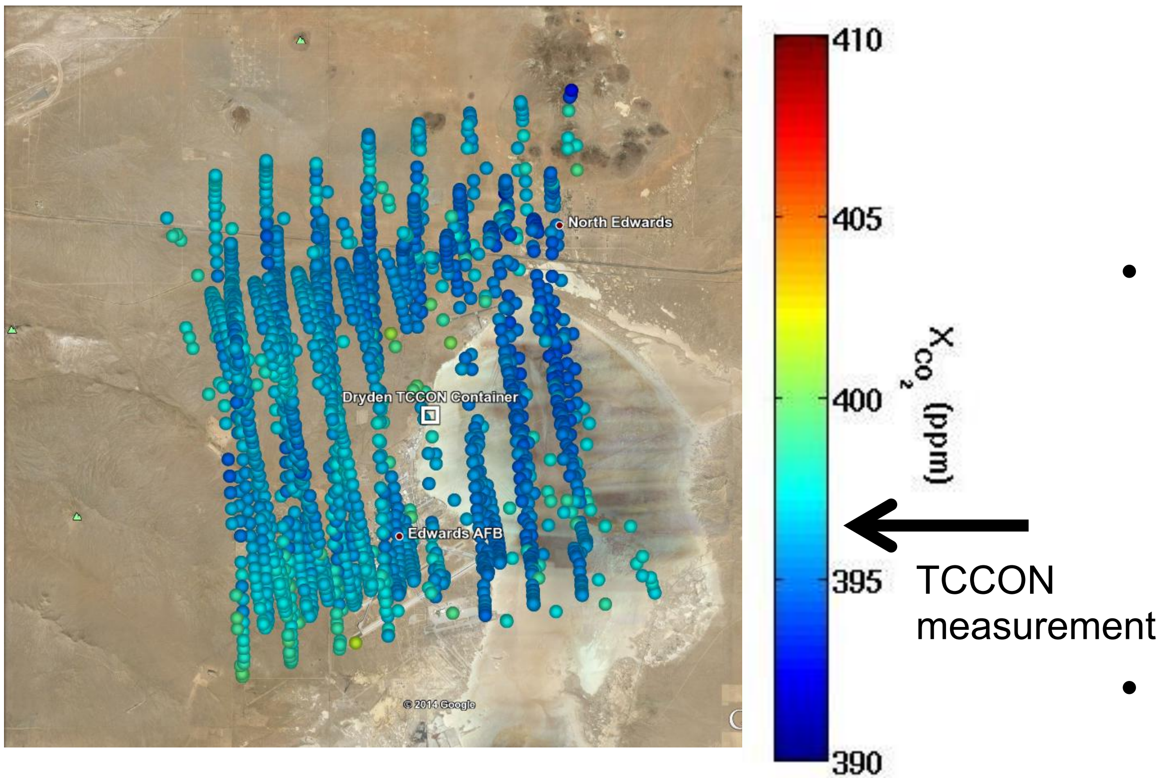


Radiance discontinuities in the raw O_2 A-band spectrum (red) have been corrected with the candidate algorithm (black)



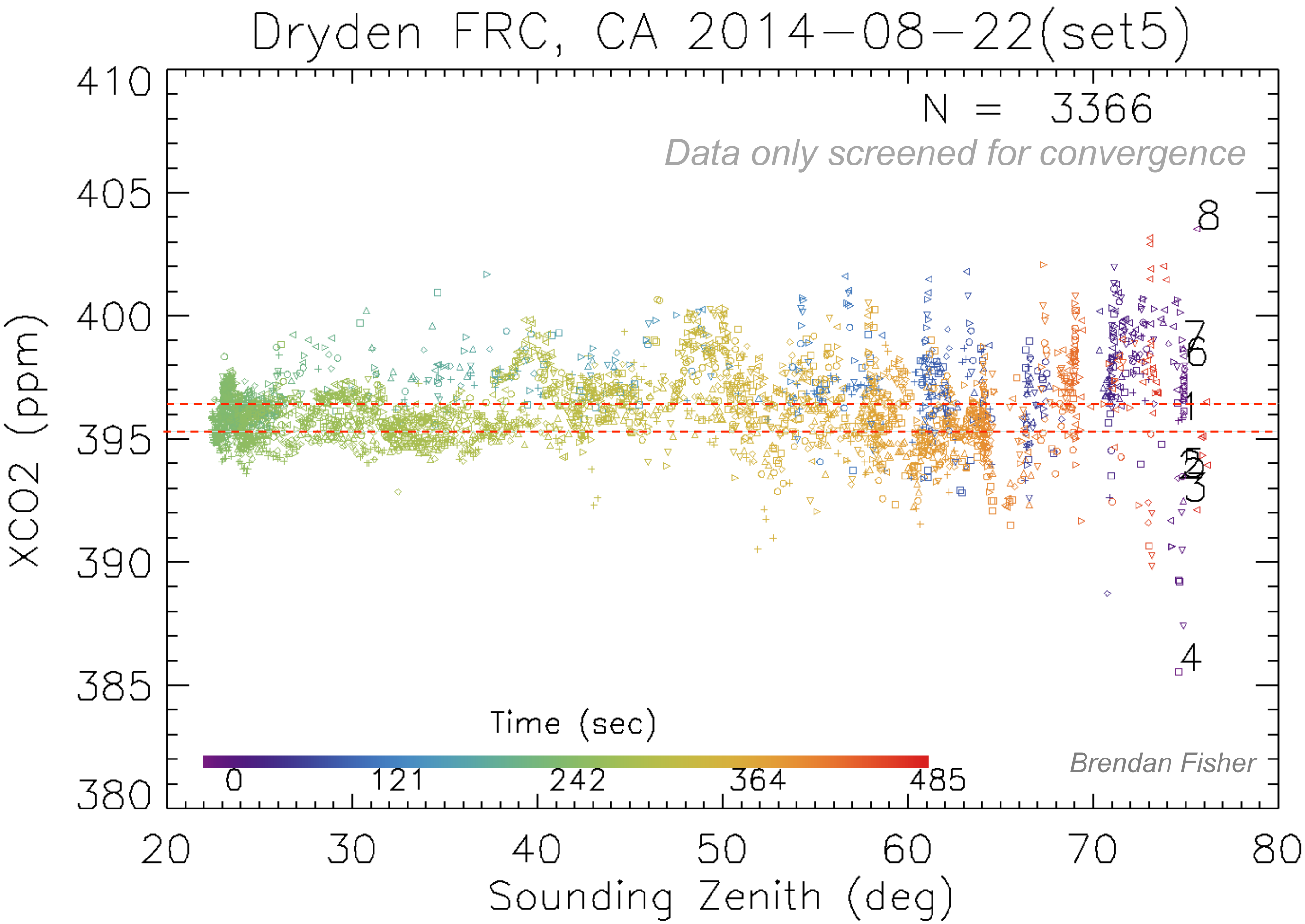
The radiance dis-continuities are also seen in the fit residuals prior to correction (blue) and after correction (red).

Target Observations over NASA-Armstrong on 8/22/2014



- OCO-2 results are being validated against ground-based measurements from the TCCON (Total Carbon Column Observing Network).
- This dense set of OCO-2 measurements were taken over NASA- Armstrong Flight Research Center near Roger's Dry Lake Bed, California.
- The OCO-2 measurements are closely grouped around the TCCON measurement.

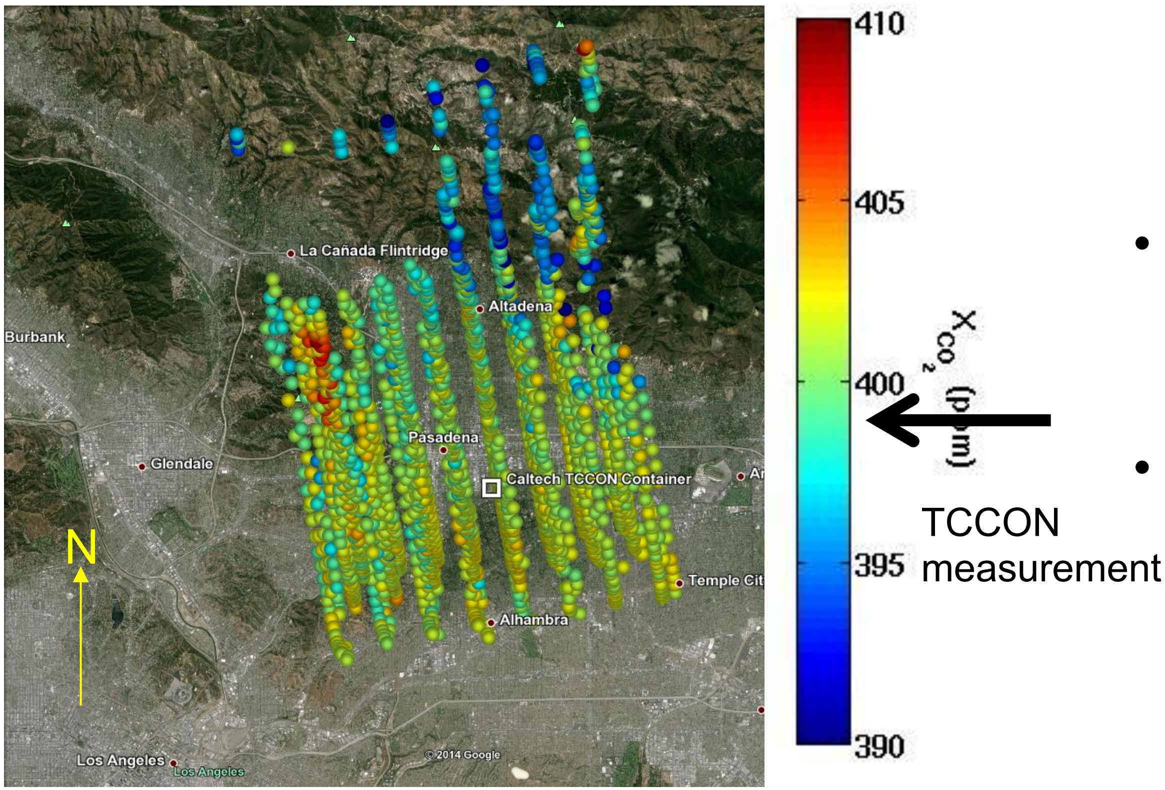
Preliminary Target Observations over NASA Armstrong Flight Center



Dryden TCCON range (1 σ) during overflight

During the overflight of the Dryden TCCON station on 8/22/2014, the station recorded X_{CO2} values near 396 ppm.

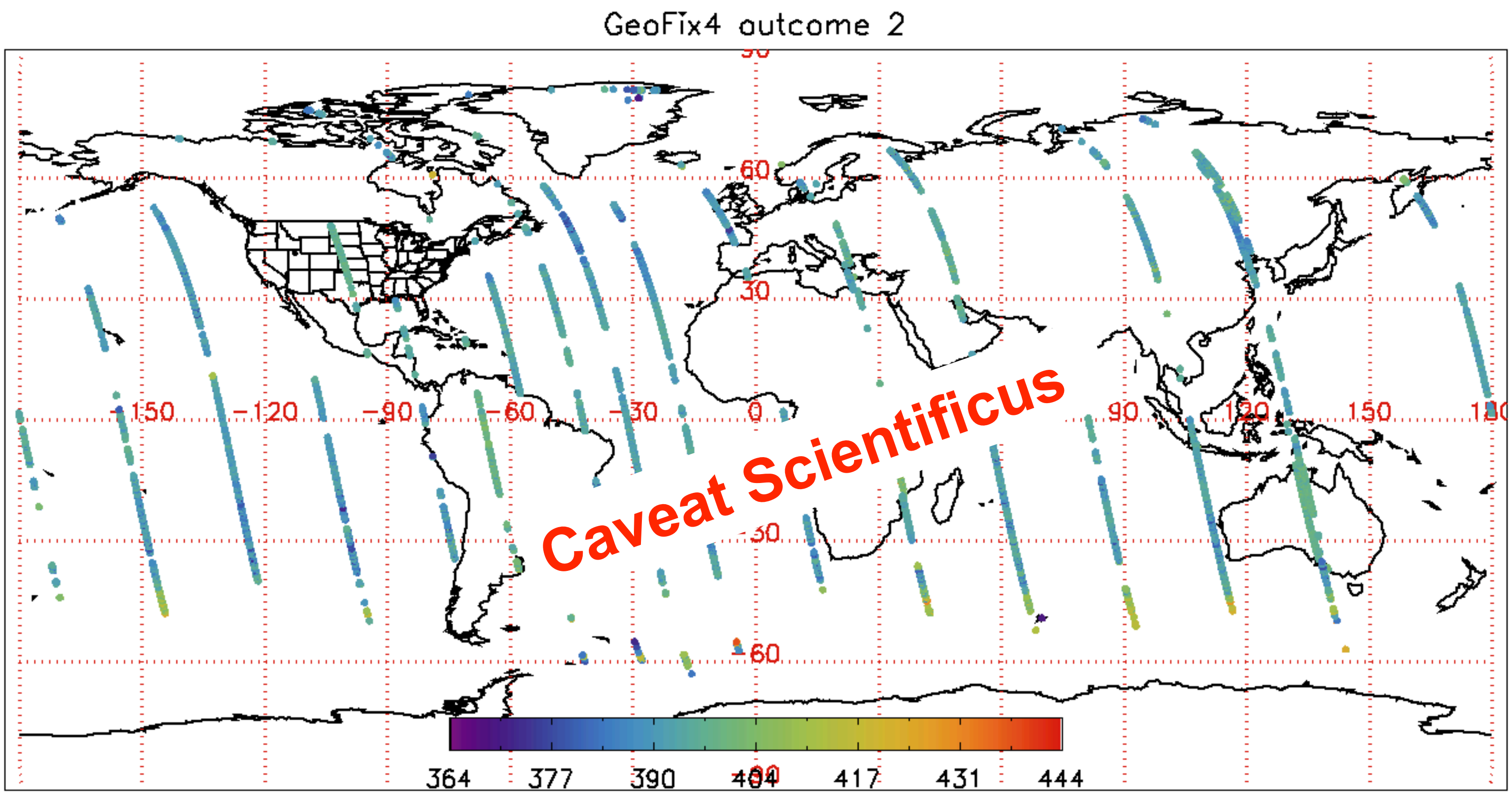
OCO-2 Measurements over Caltech site



- This dense set of OCO-2 measurements were taken over California Institute of Technology in Pasadena, CA on 5 Sept
- The agreement is quite good over central Pasadena
- The large variations seen over the high topography to the north and west of the center of the scan are likely to be spurious
  - due to pointing and air mass uncertainties.

Preliminary X_{CO2} Retrievals

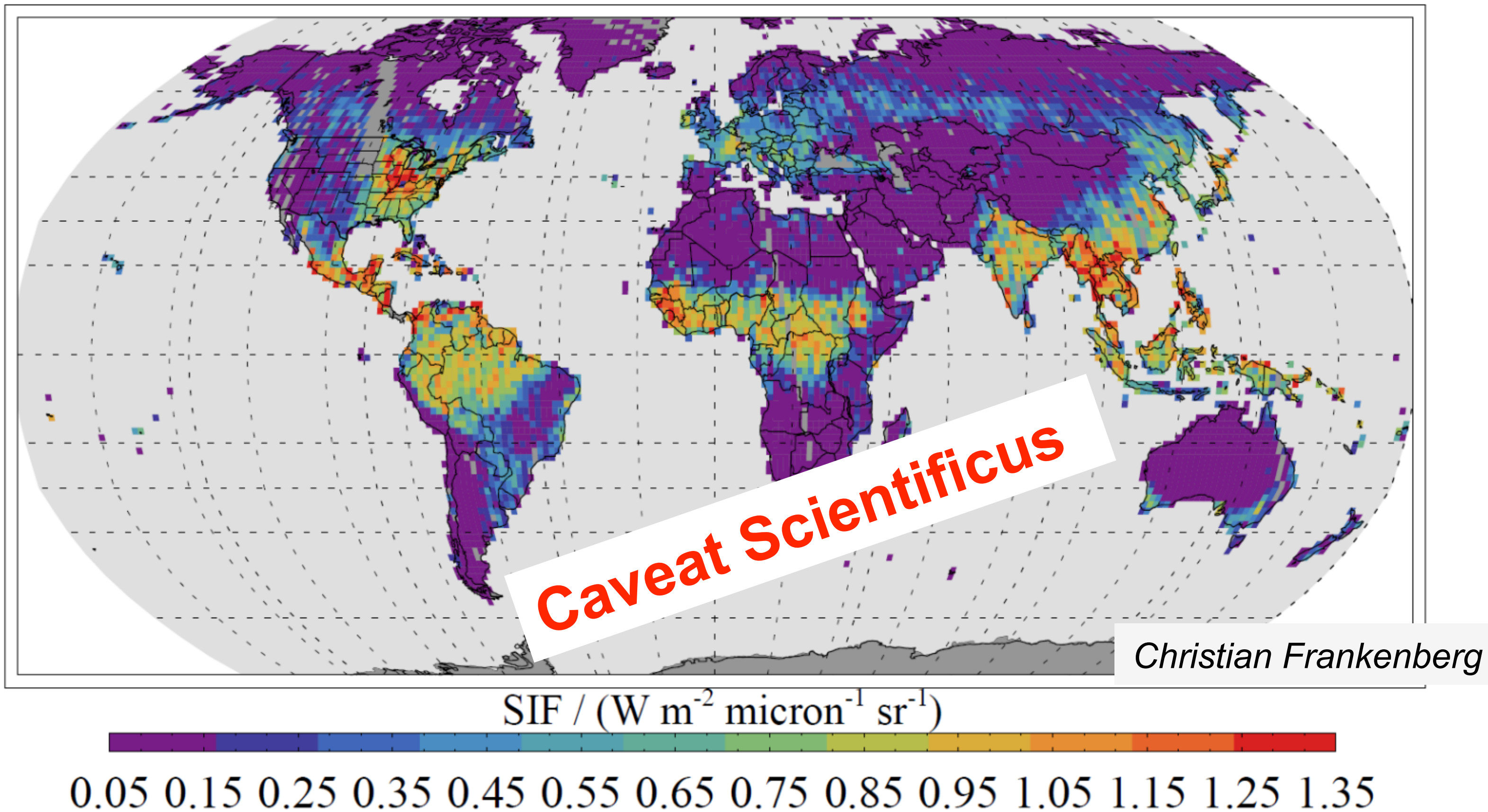
Early datasets have good geographical coverage. There is more work to go to evaluate data quality throughput statistics as a function of latitude.



A. Eldering

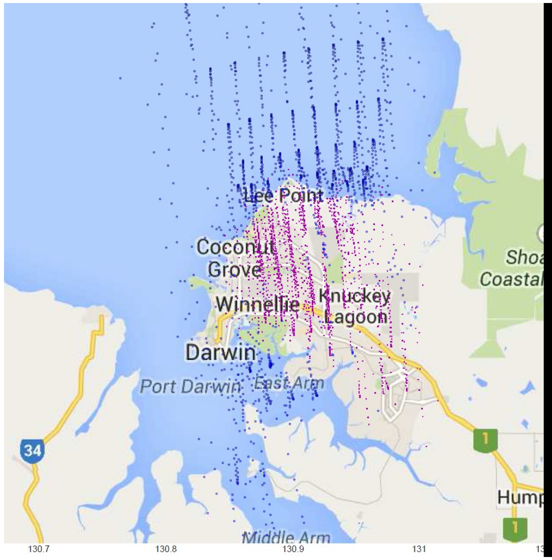
Solar Induced Chlorophyll Fluorescence: First Results

OCO−2 Solar Induced Fluorescence from current Nadir orbits



Early chlorophyll fluorescence results also show great promise.

Completing IOC: Work To Go



- Geometric Calibration
  - Coastline crossings indicate a ~1-footprint offset
- Radiometric Calibration
  - Complete analysis of RRV and Lunar Measurements
- Spectral Calibration
  - Implement modified dispersion coefficients
  - Complete testing and implementation of correction for FPA clocking errors
  - Analyze “Solar Doppler” results to establish an ILS baseline
- Updates to the Level 2 algorithm
  - Compute and implement spectral EOF’s to eliminate fixed residuals due to spectroscopic uncertainties
  - Re-tune A-Band O_2 and IMAP cloud screening algorithms for OCO-2

Status and Near Term Activities

Status

- Spacecraft Status: NOMINAL
- Instrument Status: NOMINAL
- A-Train Position: NOMINAL
  - Drag Makeup Maneuver (Expected Around November)

Near Term Activities

- 10/7: Post Launch Assessment Review (PLAR)
- 10/13: Start of Phase E – Operations
- 12/31: Start routine L1B deliveries to the GES DISC
- 3/31: Start routine L2 deliveries to the GES DISC

Conclusions

- The In-Orbit Checkout activities are proceeding largely on schedule
  - Lunar calibration confirms instrument pointing to ~150 arc-second
  - Improvements in the Dark calibration and bad pixel masks have substantially improved the accuracy of the recorded spectra
  - Nadir, Glint, and Target observation modes have been demonstrated
  - Conjunction Assessment Reviews are now a regular part of our lives
  - The functionality of the operational data processing system and science algorithm have been demonstrated
- A few issues have been identified, and are being worked, but none are expected to prevent us from meeting the Mission’s Baseline Science Objectives or its Level 1 Science Requirements.
- Routine L1B product deliveries begin by end of calendar year
- Routine L2 product (X_{CO2}) deliveries begin by end of March 2015